Joint Centre for Mesoscale Meteorology, Reading, UK

Conceptual Models of Cyclogenesis

A. Semple

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Met Office Joint Centre for Mesoscale Meteorology Department of Meteorology
University of Reading PO Box 243 Reading RG6 6BB United Kingdom
Tel: +44 (0)118 931 8425 Fax: +44 (0)118 931 8791
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Conceptual Models of Cyclogenesis

A review and unification of conceptual models used to describe the structure and evolution of mid-latitude cyclones.

Adrian T Semple

UK Meteorological Office / Joint Centre for Mesoscale Meteorology

August 1998

Abstract

Extensive studies of extra-tropical cyclones over the past sixty years have led to a plethora of conceptual models that describe the structure and evolution of storms. These conceptual (or structural) models blend observational, experimental and mathematical studies so as to represent the physical phenomena within a simple, yet flexible framework. The first three sections of this report review these conceptual models by stepping through the evolution of a mid-latitude cyclone and aim to illustrate how at each stage, conceptual models give a description of the physical processes occurring within the system. The fourth section reviews a recent cyclone classification scheme in the context of these conceptual models, and attempts to group the cyclone classes into those arising through similar mechanisms. Conceptual models are then combined with this classification scheme so as to offer a unified perspective of cyclogenesis out of which a cyclone continuum develops.

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Foreword

This review has been undertaken as the essential first stage of a project to determine how conceptual models of weather systems might be used in the development of operational NWP models. Conceptual models aim to give a concise account of observed structures, not to explain why they occur – or even to demonstrate their own dynamic and thermodynamic consistency. Most relevant papers, however, include attempts at explanation, often (it would seem) for connective or mnemonic reasons. For similar reasons, this review includes such 'explanations' although it is clear that some of them are not rigorous in a dynamical sense.

Foundations for more rigorous dynamical explanations are offered by various forms of quasi-geostrophic theory, and by the somewhat more comprehensive potential vorticity (PV) view; for discussion and further references see the papers in the December 1997 issue of *Meteorological Applications* (published by the Royal Meteorological Society).

One of the important by-products of the present review is a unified picture of conceptual models (given in Section 5) which emphasises the component elements of the models and shows the particular types as consequences of the various ways in which the component elements may combine and interact. This unified picture makes useful synthesis of the conceptual model view and the PV view a real possibility for the future.

Andy White
Theory Applications Group Leader, JCMM

1. Overview : Conceptual Models

[1]**concept** *n.* **1** a general notion; an abstract idea. **2.** *Philos.* an idea or mental picture of a group or class of objects formed by combining all their aspects.

model *n.* & *v.* **1** a representation in three dimensions of an existing person or thing or of a proposed structure. **2** a simplified description of a system etc., to assist calculations and predictions.

Cyclonic depressions, or cyclones, develop in the atmosphere on a variety of scales. The initiation or strengthening of cyclonic circulation is described by the term ***cyclogenesis*** (Meteorological Glossary, 1991), whilst the broader evolution of the cyclone (its formation, deepening, occluding and filling up) is collectively referred to as its ***life cycle.***

Historically, the study of these systems has been approached in two different ways, with what will be referred to in this review as 'single' and 'multi' body schemes, (a 'body' being defined as a separate cloud-inducing element in the synoptic scale flow). Thus,

- ***Single body cyclogenesis*** is a treatment based on the assumption that cyclones develop from a single element in the synoptic scale flow.
- ***Multi-body cyclogenesis*** assumes that cyclones develop out of interactions between localised separate-entity disturbances in the synoptic scale flow.

In either scheme, elements may originate as weak perturbations within an atmospheric flow that is otherwise uniform at some particular level of the atmosphere. The multi body scheme then requires that at least two such separate disturbances interact in some way.

Technological advances in satellite imagery during the past few decades have enabled the identification of cloud signatures indicative of cyclogenesis to become possible. It has been observed that cloud development during the life cycle of an archetypal cyclone commences with the formation of a crescent-shaped band of dense cloud situated largely on the cold side of the surface fronts[2] (Fig1.1, stage 1). This cloud has been produced by ascending air from the warm side of the front, and is mostly stratiform in nature. Precipitation is widespread north of the warm front.

As the cyclone develops, the cloud shield often expands towards the west and southwest of the surface low centre (Fig1.1, stage 2) until it resembles a comma punctuation mark. The head of the comma-cloud (the cloud-head) is represented by the northern and western parts of the cloud shield (Fig1.1, stages 1 & 2).

The westward and southward extension of the cloud shield continues as the cyclone develops further with the production of shallow stratiform cloud (Fig1.1, stage 3) within the boundary layer. This is accompanied by the development of a cloud-free zone (Fig1.1, labelled) intruding into the cloud head region.

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[1] Dictionary definitions from the Concise Oxford Dictionary, ninth Edition, 1996

[2] The boundary between the two air masses in a developing cyclone is referred to as a *front* which describes the transitional zone of finite width (~100 km) and depth (~1km) (Bjerknes and Palmen, 1937). The frontal structure of a developing cyclone does not necessarily extend continuously from the surface to the tropopause (usually defined by a discontinuity in potential vorticity) and there may be marked differences between upper and lower level fronts.

Ultimately, the system becomes a large swirl of cloud surrounding the low centre.

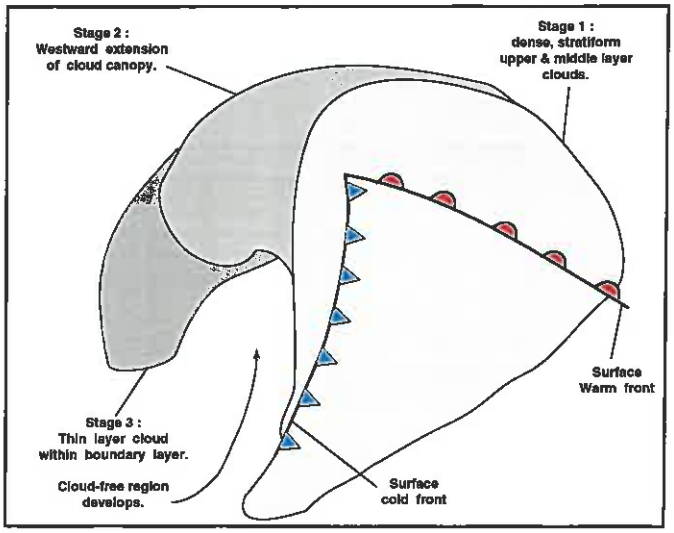


Figure 1-1 Evolution of cloud distribution in a developing cyclone. (Adapted from Carlson, 1980)

More detailed analyses have taken these observations further and enabled a conceptual model of cyclone-frontal evolution to be proposed (Shapiro and Keyser, 1990). This model takes the single body approach and postulates four basic phases of a cyclone in its life cycle.

1. A continuous broad baroclinic front.
2. Frontal fracture in the vicinity of the cyclone centre.
3. Frontal T-bone, and bent-back warm front.
4. Warm-core frontal seclusion in which warm air becomes entrapped at the centre of the cyclone.

The T-bone phase is representative of the mid-point of a cyclone's life cycle, and is shown along with the other phases in Figure 1-2.

These four stages represent an idealised view of how a cyclone can develop from birth to maturity. However, it has become apparent that this *single body* approach does not always account for many crucial aspects in a cyclone's development and structure, and that a more comprehensive picture in the investigation of these systems is obtained with the *multi-body* approach.

Both the complex mechanisms of airflow and the detailed evolution of extra-tropical cyclones in the multi-body approach can be represented successfully through the use of conceptual models - simplified images of the weather systems that incorporate their essential physics and structures. The main descriptive element used in the conceptual models of weather systems is the *conveyor belt.* These describe the three dimensional airflow in a *relative system* and provide a firm basis for the description of cyclonic depressions. The concept of conveyor belts is described in Sec. 2.

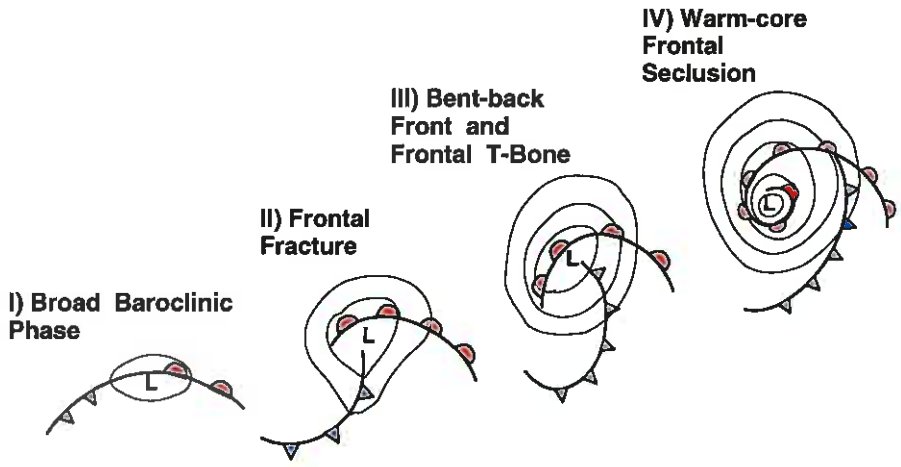


Figure 1-2 Model of frontal-cyclone evolution proposed by Shapiro and Keyser, 1990. (Based on a figure from Shapiro and Keyser, 1990)

In Sec. 3, mid-latitude cyclones are discussed in detail using conceptual models with a consideration of the characteristic stages that follow each other in a storm's life cycle.

Classification schemes based on the systematic differences between cyclones may then be seen simply as a way of specifying how the cyclone has evolved in order to develop into a mature vortex. The classification scheme proposed by Young (1993) is detailed in Sec. 4 and presented within this context so that the relationship between all the '*families*' of cyclones is evident.

Sec. 5 then aims to draw all the above information together, by viewing differences in cyclone evolution *not* as differences in class of cyclone but merely as differences in the mechanism required for the cyclone to develop to that point. This may be considered as a subtle change of approach and does require some degree of simplification of systems, but it provides a more unified view of cyclogenesis and shifts the emphasis more onto the fundamental dynamical mechanisms acting throughout the cyclone. The result is a 'continuum' of cyclone types which allows for degrees of particular cyclone characteristics to be observed when progressing from one end of the spectrum to the other. The classification scheme of Young is then born out in the scheme as distinct boundaries within the continuum.

It is hoped that the unification scheme developed here removes the need for classes of cyclones to be recognised and instead reduces the problem back to its roots – the interaction of a number of component elements. With this hypothesis in place, a route for the use of conceptual models in the NWP is foreseen.

2. Conveyor Belts

2.1 Introduction : System-relative airflows

When air ascends/descends adiabatically, its potential temperature remains constant so that ascending or descending air may be treated as flow along surfaces of constant θ. These surfaces are termed *isentropic surfaces* since a surface of constant θ is also one of constant *entropy*. Isentropic analysis requires the use of two such parameters to describe the flow: θ_w (the wet bulb potential temperature) surfaces if the air is saturated, and θ surfaces if the flow is dry. Cloud formation can be associated with regions of ascent of air within the sloping portions of these surfaces.

In the case of weather systems, isentropic analysis is carried out within *a co-ordinate system travelling with the system* in order to correctly interpret the cloud and precipitation bearing systems. This assumes that the system moves steadily without change of speed or shape so that vector subtraction of the system's velocity enables airflow relative to the system to be determined. This system-relative framework is often referred to as "Relative Flow Isentropic Analysis".

The term *conveyor belt* may then be used to describe the three dimensional large-scale motion of air moving along the isentropic surfaces in *the system-relative framework*. The depth of the conveyor belt will be made up from a series of isentropic surfaces at lower and higher altitudes but all with the same gross flow pattern (although the flow within the conveyor belt may vary from level to level). The series of isentropic surfaces therefore gives the conveyor belt a three dimensional structure such that they are commonly 1-3 km deep, 200-300 km wide and often thousands of km long.

In temperate latitudes conveyor belts are generally associated with frontal zones and play a crucial role in the development of conceptual models of weather systems. There are two types of conveyor belt that are classified by the relative temperature of the air within them: the Warm Conveyor Belt (Harrold 1973) and Cold Conveyor Belt (Carlson 1980).

2.2 The Warm Conveyor Belt

2.2.1 Introduction.

The Warm Conveyor Belt (WCB) is the primary cloud producing airflow in extra-tropical cyclones. It represents airflow in which large quantities of heat, moisture and momentum are conveyed poleward and upward ahead of the cold front within mid-latitude frontal systems. The wet bulb potential temperature of the WCB varies according to the time of year and the system's origin. For mid-latitude cyclones, it is characterised typically by $\theta_w \sim$ 17-19°C in summer and $\theta_w \sim$ 10-11°C in winter, whilst polar systems may often exhibit θ_w<6°C. However, in all cases it is the relative temperature of the WCB to the remainder of the system which distinguishes it as a discrete entity of a cyclone.

The WCB rises from the lower troposphere at its southern end into the upper troposphere at its northern end - the ascent being part of a thermally direct circulation in which warm air ascends and cold air descends. The airflow accelerates as it rises, producing a jet maximum at upper levels. As precipitation is heaviest where air ascends rapidly after reaching saturation, considerable precipitation is

generated in the WCB flow in the low to middle troposphere. WCBs therefore produce low and medium level clouds, with a belt of cirrus in the upper troposphere that dissipates at its leading edge.

A distinctive feature of the cloud belts associated with WCBs is the sharp edge of the western and poleward high cloud. This edge is a result of the *deformation zone* in the relative system produced by the advance of the WCB acting against air being brought down from the upper troposphere/lower stratosphere. For this reason, the deformation zone is also the location of the maximum wind strength within the WCB. The left hand edge of the WCB (and associated sharp cloud boundary) may be either behind or ahead of the surface cold front depending on whether the air in the WCB has a rearward (ana) or forward (kata) component relative to the advancing cold front.

2.2.2 Rearward Sloping Ascent of The Warm Conveyor Belt.

When air in the WCB has a component rearward relative to the motion of the approaching cold front, the WCB air rises above the cold air of the cold front (Figure 2-1). This scenario corresponds to the classical type of cold front, and is often referred to as an *ana-cold front* (Bergeron, 1937).

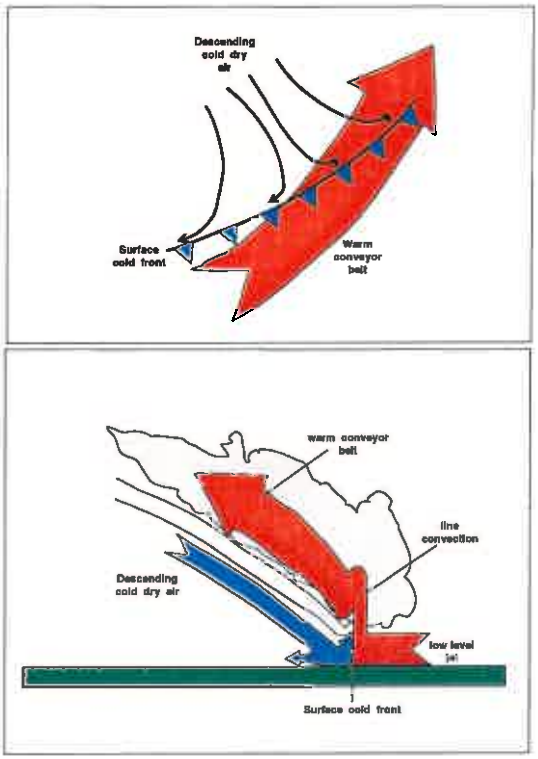


Figure 2-1 Conceptual model of a classical ana-cold front in which the warm conveyor belt undergoes rearward sloping ascent relative to the approaching cold front : (TOP) Plan view; (BOTTOM) Vertical cross section perpendicular to the surface cold front. (After Browning 1990).

Where the WCB is still in contact with the earth's surface, it is characterised by a low level jet immediately ahead of the surface cold front (Browning, 1990). These low level jets have maximum velocities typically of ~30 ms^{-1} (although they can be >40 ms^{-1}) and occur at heights of ~900 mb. The warm air of the WCB is then lifted abruptly at ~7 ms^{-1} (Browning, 1990) within a narrow strip ahead of the cold front. This produces a band of heavy precipitation associated with upright line convection at the surface cold front. After 2-3 km of upright ascent, the air rises in a slantwise fashion at a lower velocity of ~0.2 ms^{-1} (Browning, 1990) above the wedge shaped cold air behind the cold front. With a large proportion of the moisture within the

WCB having been removed earlier and with a lower rate of ascent above the wedge of cold air, the precipitation behind the surface cold front is correspondingly lighter.

2.2.3 Forward Sloping Ascent of The Warm Conveyor Belt

In the forward sloping configuration of the WCB, dry air from the middle troposphere with a horizontal velocity larger than that of the surface cold front overruns the WCB ahead of it (Figure 2-2). The important property of the air overrunning the warm conveyor belt is that it is very dry and therefore of low θ_w. However, this does not necessarily mean that its temperature is lower than that of the WCB, since as it descends and expands adiabatically it will warm up. It is for this reason that the situation is better described in terms of humidity and θ_w rather than temperature (Browning and Monk, 1982).

This situation, in which air from the middle troposphere overlies air of the WCB may be potentially unstable - warm air from the WCB may become unstable once it has been lifted sufficiently above the cold air. Given suitable dynamical forcing, it may therefore be favourable for convection to occur into the overlying low θ_w air, and a strong band of precipitation ahead of the surface cold front is produced. The position of this convection consequently lies at the leading edge of the dry θ_w air and constitutes an "upper-cold front" which is ~100 km (Browning and Monk, 1982) ahead of, and clearly separate from the surface cold front (more correctly the upper-cold front should be referred to as an upper-humidity front). Behind the heavy rain of the upper cold front is typically a *shallow moist zone* (SMZ) (Browning, 1990) characterised by patchy rain or drizzle. The SMZ also exhibits a low cloud base with poor visibility at the surface.

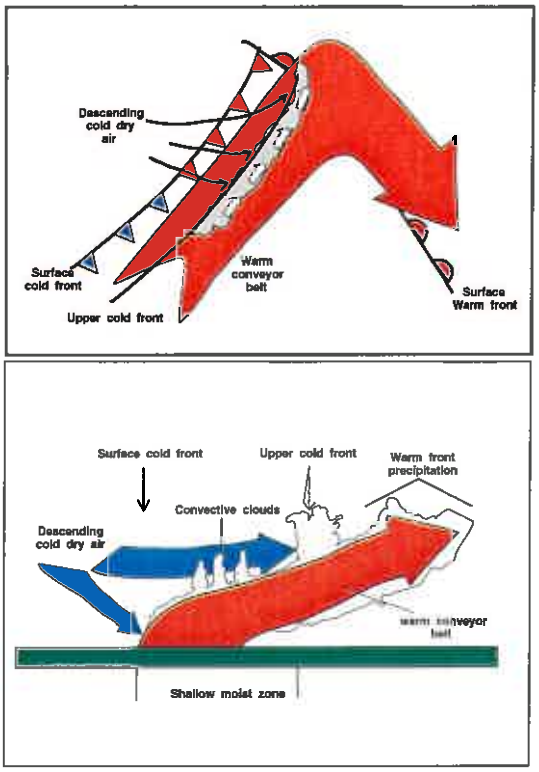


Figure 2-2 Conceptual model of a kata-cold front in which the warm conveyor belt undergoes forward sloping ascent relative to the advancing cold front. (TOP) : Plan view; (BOTTOM) : Vertical cross section. (After Browning 1990).

When the WCB is in this configuration, the cold front is referred to as a *kata-cold front* (Bergeron, 1937). Also, because of the existence of an upper-cold front ahead

of the surface cold front, this configuration is also often referred to as a *split cold front* (Browning and Monk, 1982). A kata-cold front will normally have a surface warm front ahead of it, although it is possible for the upper cold front to extend far enough ahead so that it is also ahead of the surface warm front.

2.3 The Cold Conveyor Belt

The Cold Conveyor Belt (CCB) originates from cold subsiding air to the north-east of a developing cyclone and is characterised typically be several degrees lower than the associated WCB of the system. It develops at low levels ahead of a warm front and travels westwards so as to undercut the WCB travelling poleward above it (Figure 2-3). As it does so, it attains moisture in the boundary layer both by contact with the surface and by evaporation of precipitation falling into it from the WCB. In this way, the CCB redistributes moisture within the system. As it continues its westward motion, the CCB ascends along a lower isentropic surface than that of the WCB until it emerges north of the surface low. If the CCB continues to ascend it may turn anticyclonically (in a similar way to that of the WCB as a result of upper level winds) and eventually flow parallel to the WCB.

Cloud produced by the ascending CCB is mainly confined to low and medium levels, below the cloud band associated with the WCB. However, the approach of the two air masses associated with the CCB and descending air from the upper troposphere (Sec. 3.1) produces a confluence zone at the western end of the CCB and the highest cloud tops in the CCB cloud band.

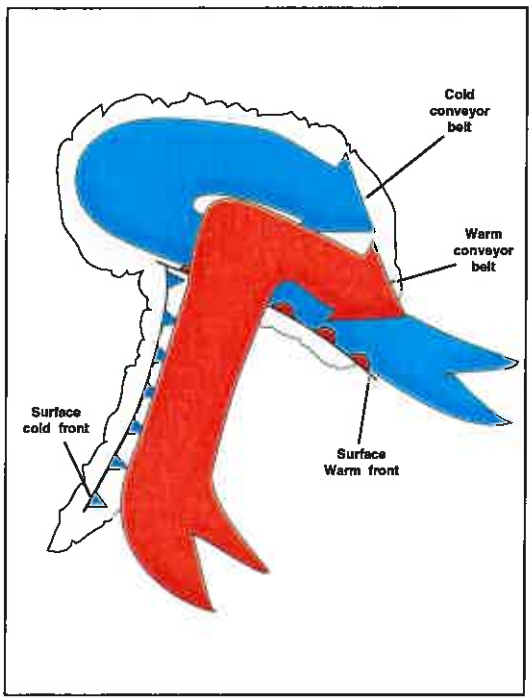


Figure 2-3 Conceptual model of the two major airflows in a cyclonic depression : the warm and cold conveyor belts. (Adapted from Bader et. al 1995).

If the CCB emerges to the west of the WCB, the CCB may bifurcate at the confluence zone with part of it ascending anticyclonically and part of it descending cyclonically around the cyclone centre. It is this process that in part leads to the development of a comma cloud head and indicates that cyclogenesis is proceeding (See Sec. 3.2.3.3 for full details).

3. The Life Cycle of Extra-tropical Cyclones

The onset of cyclogenesis and the distribution of the air flow in the upper troposphere are intimately connected: cyclones commonly develop on the leading edge of synoptic scale upper troughs where there are regions of ascent and upper level forcing in the vicinity of frontal zones. Cyclogenesis may therefore be studied on the basis of atmospheric flow around such a trough in the upper troposphere, with the role of jet streaks[3] being crucial. Sec 3.1 traces the evolution of the jet streaks as cyclogenesis proceeds. Sec. 3.2 then details each stage in the evolution of a cyclone's lifecycle using the concept of conveyor belts and within the framework of the jet streaks already set up.

3.1 Jet Streak Development and Labelling Convention

The configuration of the jet stream and its associated maxima (jet streaks) is instrumental in the development of a mid-latitude cyclone. Figure 3-1 shows a case (analysis from Young *et. al.*, 1987) in which two jet streaks are identified in association with a synoptic scale upper trough.

The convention used in this report for assigning the labels J1 and J2 to jet streaks uses the trough axis as a reference point. The jet streak downstream of the trough axis is always assigned J1, whilst the occurrence of a second jet streak upstream of the trough axis is then assigned J2. Both jet streaks have similar properties since they are both a core of high level winds with similar origins and are both associated with high potential vorticity on their poleward sides. This convention allows J2 to take up its correct position within later stages of cyclone development and is consistent with that used by Bader *et al.* (1995), when labelling was used.

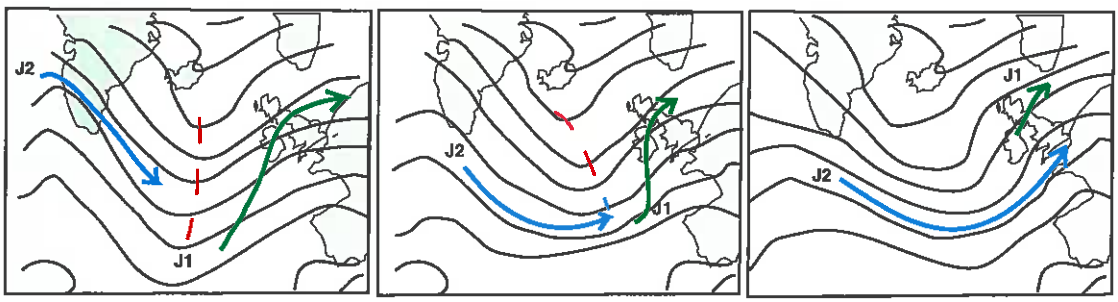


Figure 3-1 Schematic of system-relative jet streaks associated with an upper level trough (300mb) and associated developing cyclone for early stage (a) to more mature stage (c). J1 is influential on early cloud structure of the cyclone (a) and originates downstream of the trough axis (red dashed line). J2 originates upstream of the trough axis and is the origin of the dry intrusion airstream which influences the subsequent cyclogenesis (c). These two jets will have varying proximity to one another in other cases of cyclogenesis, depending on the amplitude of the trough. Black lines show the geopotential height structure of the trough. (Adapted from a study by Young et al., 1987).

Jet J1 originates from the upper troposphere/lower stratosphere to the south and is influential in the initial cloud development downstream of the trough axis. Jet J2 originates from the upper troposphere/lower stratosphere to the west and descends behind the developing cyclone from a stage that in some cases may even precede leaf cloud development (Sec. 3.2.2). J2 is observed to have a particularly significant influence on the developing cloud pattern throughout the life of the storm and constitutes a major airflow in a depression - the *dry intrusion.*

[3] Relatively small and short-lived cores of intense winds within the larger scale long-lived jet stream.

In cases where two distinct jet streaks exist from the outset, their relative proximity will be dependent on the amplitude of the upper trough. This may therefore be a factor in determining the speed and degree of cyclogenesis: explosive cyclogenesis will require the close proximity of intense jet streaks J1 and J2.

3.2 Cyclone Evolution

The most recent and comprehensive study of cyclogenesis was carried out by McLennon and Neil (1988) and continued by Young (1993). Young identified three factors influential in the development of a cyclone when considering the atmospheric flow distribution:

- ***The airflow pattern through a synoptic scale trough in the upper troposphere.***
- ***The position of the jet streaks relative to the cloud formations.***
- ***The presence of an area of enhanced convection in the cold air upstream of the trough axis prior to cyclogenesis.***

In most cases, the presence of a cloud system upstream of the trough axis necessitates the consideration of a *multi-body* system - through interactions the cold air feature may induce cyclogenesis where none would have arisen in a single-body system. This synoptic setting provides a framework around which the possible evolution of a cyclone may be built. The life cycle of the cyclone can then be divided into phases that often appear in sequence as the depression develops:

1. ***Initial cloud features.*** The formation of enhanced convective cloud and/or a polar front cloud band.
2. ***The leaf cloud.*** The evolution of a sharp S-shaped poleward edge to the polar front cloud band or a discrete 'leaf-shaped' cloud area within a pre-existing cloud structure.
3. ***The comma cloud.*** The development of the leaf cloud into a comma shape.
4. ***The cloud head.*** Evolution of the head of the comma cloud.
5. ***Frontal fracture.*** A fragmentation of the main cold front in the vicinity of the low pressure centre. This process is accompanied by the development of the dry slot.
6. ***Split front development.*** The formation of an upper cold front in association with the surface cold front.
7. ***Mature vortex.*** A well defined swirl of cloud around the low pressure centre.

The following sections give an overview of these key developmental stages and utilise the conceptual models that describe the evolution of extra-tropical cyclones.

3.2.1 Initial Cloud Development

3.2.1.1 Enhanced Convection in Cold Air Upstream - The Polar Trough

Large scale (long-wave) upper troughs (as shown in Figure 3-1) often have short-wave polar troughs upstream of their axis. Air flowing around the *short-wave polar trough* is typically deep, cold and highly unstable with considerable vertical shear. Upstream of its axis, this produces open cellular clouds blown into elliptical shapes by the direction of airflow. Downstream of its axis is an area of enhanced ascent so that clusters of large cumulus clouds form in the deep cold unstable air. The cloud

amount being produced will increase with time and individual clusters will fuse together producing a single, larger mass of cloud.

If the region in which the enhanced convection is taking place is also a region of strong baroclinicity, the development of cloud in the cold air upstream may also be interpreted as the ascent of a warm conveyor belt (Sec. 2.2) ahead of the cold front associated with polar trough.

3.2.1.2 Polar Front Cloud Band and Frontal waves

The leading edge of the cold air moving round the base of the long-wave upper trough has a cold front associated with it. As the cold air advances, warm air is forced to ascend in the form of a warm conveyor belt (Sec. 2.2) and a frontal cloud band develops. The cloud band develops on the warm side of the jet streak J1.

However, if the polar front cloud band is orientated with its major axis along the flow of a diffluent trough, J2 may come along the cold side of the cloud band and the role of J1 in cyclogenesis is reduced. In this case, the cloud band will not be shaped into a leaf cloud (Sec. 3.2.2) but will develop directly into a comma cloud through the action of J2 (Sec. 3.2.3).

Frontal waves may also form along the length of the polar front, and are observed as convex bulges on the cold side of cloud band. The waves develop in frontogenetic regions where the solenoidal circulation across the front causes pressure to fall on its warm side. The associated upper level divergence may then develop a shallow surface low pressure system, and provide a means of cyclogenesis without the requirement of J2. A polar front may therefore develop through a wave stage and directly into a comma cloud (Sec. 3.2.3) without the requirement of J2. However, a low formed in this way will not attain much severity unless J2 (with its associated high potential vorticity) arrives and reinforces the upper level divergence.

3.2.2 Leaf Cloud development.

If the jet stream (J1) cuts into the polar front cloud band, a convex-poleward bulge will develop in 75% of cases (Weldon, 1986) and the cloud evolves into a *baroclinic leaf* - an elongated stratiform cloud with a sharp S-shaped poleward edge (see Figure 3-2). The leaf generally forms on the forward side of an upper trough and moves parallel to the jet (J1) with the precise shape of the leaf being determined by the exact orientation of the jet (J1). By the time J1 has initiated the development of the leaf cloud, J2 (the dry intrusion) has often approached and encroaches upon the rear of the leaf cloud. The dry intrusion airstream has a history of descent with marked diffluent flow at its leading edge so that the flow bifurcates at the jet exit.

- Air at the jet left exit turns cyclonically and ascends at a rate of ~4 mb h^{-1}. This ascent is forced by a region of strong positive vorticity advection within the region of cold advection (Young, 1987). This airflow, north of the jet axis is of *stratospheric* origin (Danielsen, 1966).

- Air at the jet right exit turns anticyclonically and descends at a rate of ~7 mb h^{-1} and occupies a region of negative vorticity advection (Young, 1987). This airflow, south of the jet axis is of *tropospheric* origin (Danielsen, 1966).

The bifurcation of the airflow produces a characteristic hammer-head distribution (Figure 3-2) for the dry intrusion which can be present several hours before leaf cloud formation is complete (Young *et. al*, 1987).

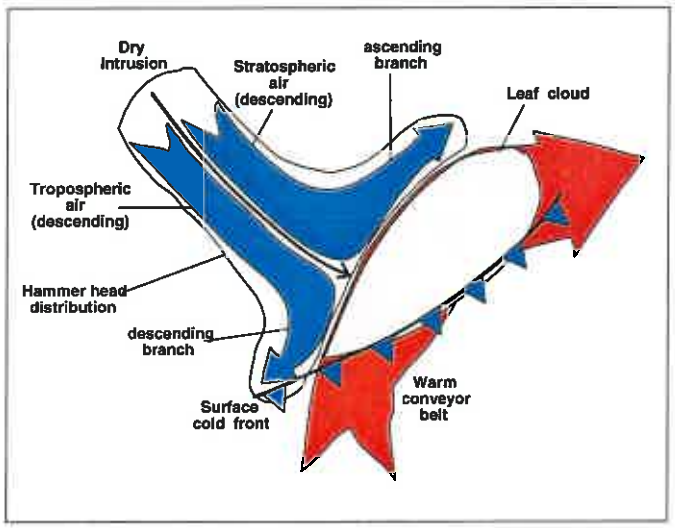


Figure 3-2 Conceptual model of a leaf cloud. The position of the dry intrusion airstream (J2) with its characteristic hammer head shape is shown relative to the leaf cloud. The jet stream J1 (not shown) moves along the poleward edge of the leaf cloud. (After Young et. al, 1987)

The rate of arrival of the dry intrusion at the rear of the developing cyclone depends on the proximity of the two jet streams J1 and J2 in the initial situation. Rapidly deepening cyclones involve an early involvement of the dry intrusion during cyclogenesis, so that the relative strength and proximity of the two jets may be an early indication of the severity of the developing storm. A vorticity centre will be situated at 500 hPa on the cold (left) side of the leaf and the cloud band will start to rotate, during which time the WCB intensifies. The surface low is often located under the leaf and near the warm (right) side of the cloud band.

A leaf cloud of smaller size may also form in the cold air within the secondary baroclinic zone associated with the short-wave trough.

3.2.3 Comma Cloud Development

3.2.3.1 Overview

The comma-cloud is so called because it resembles a comma punctuation mark, and is characterised by a wide head and a narrow tail. In reference to the importance of the formation of the head of cloud, the comma-cloud formation is often referred to as the cloud-head stage. Two extremes of comma-cloud development may be identified in the cyclogenesis process (Figure 3-3) and may be referred to as type A and B comma clouds[4] (Bader *et al.*, 1995).

- *Type A comma-cloud.* The jet streaks (J1 and J2) cross the sharp rear edge of the upper cirrus cloud comprising the comma body, but at a level above the lower cloud of the developing cloud-head. As the cyclogenesis proceeds, the WCB and CCB at the cloud-head will ascend in tandem, and a type B comma may develop.

[4] Type A and B cyclones referred to here do **not** correspond to Petterssen Type A and B cyclones (Petterssen and Smebye, 1971). The Petterssen classification refers to the **origin** of cyclogenesis: Type A cyclones are formed from an amplifying frontal wave and produce kinetic energy through a reduction in low level baroclinicity. Type B cyclones are initiated through a disturbance in the upper troposphere. The labels of A and B used by Bader et al. (1995) describe the **structure** of the cyclone at some stage in its evolution.

- *Type B comma-cloud.* For this development to occur there must be significant diffluence over the region between the comma head and tail (i.e. the characteristic hammer-head distribution of the dry intrusion (J2) is fully formed). The cloud band of comma-head and comma-tail is then continuous. J1 is now reduced to a wind maximum in the north of the cloud head.

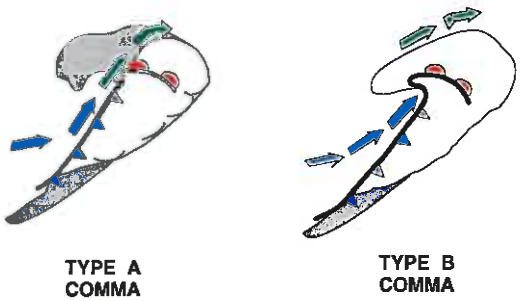


Figure 3-3 Type A and B comma clouds. Type A comma clouds are characterised by warm clouds tops (darker shading) in the developing cloud head. Jet J1 (green arrows) and the advancing J2 (blue arrows) pass continuously on the poleward side of the cloud body and above the level of the cloud head. Type B comma clouds are characterised by a more developed cloud head which separates the two jet streaks J1 and J2. (Based on figures from Bader et. al 1995)

The precise shape of the comma-cloud is therefore dependent on the relative airflow within the system, the stage of evolution of the system and the configuration of the jet streaks. The formation of a comma cloud of either type is dependent on the initial cloud system, of which there are three basic situations depending on the involvement of a cold air feature.

1. ***Development of a Comma cloud from the polar front cloud band.*** When the comma cloud develops out of the main frontal cloud band due to the presence of J2, the comma cloud produced is a Type A comma cloud (Sec. 3.2.3.2) and may subsequently develop into a Type B comma cloud. Alternatively, in the absence of J2, the polar front may develop through a frontal-wave stage. In this case a Type B comma cloud will be produced directly (a consequence of the different mechanisms involved, Sec. 3.2.1.2). In either case, the process is accompanied by the surface low moving from the warm side of the polar front cloud band to the cold side near the cloud's sharp boundary.

2. ***Development of a Comma cloud in the cold air feature.*** Providing the enhanced convection of the cold air feature is in a region of strong baroclinicity, a comma-cloud may develop as it moves into the downstream region of the upper trough. The comma cloud produced in this way is a Type B comma cloud as its cloud shield from head to body is continuous.

3. ***Dual leaf clouds.*** An elongated area of layered cloud possessing some degree of baroclinicity and lying poleward of the main frontal cloud band, may sometimes constitute a second leaf cloud. The second leaf cloud may develop upstream in the cold air or be formed from the cloud of an old front. In any case, the two cloud bands merge to form a single cloud system. Again, the cloud shield is continuous from head to body (type B).

3.2.3.2 Comma cloud evolution

The importance of the jet streaks in the initial stages of a cyclone has already been considered in Sec. 3.1. As early as the leaf cloud stage, J2 may have reached the

rear of the developing storm (Figure 3-2) and rapidly becomes the dominant jet streak of the system, whilst J1 is reduced to the northern region of the cyclone. The exit of Jet J2 then lies along the rear of the cloud system in a hammer-head formation (see Figure 3-2), so that its location is directly behind the cold frontal zone. Associated with the left exit of J2 is a region of cyclonic development which will start to deform the northern part of the cold front into a 'bent-back' structure (Figure 3-4(a)).

The surface cold front (Figure 3-4[a(iii)]) may then be divided into three distinct regions according to the frontal analysis of Browning *et al.*, (1997) (See Sec. 3.2.4.1 for alternative frontal analysis).

- ab. A sharp ana-cold frontal region often characterised by line convection.
- bc. A diffuse frontal zone.
- cd. A second sharp ana-cold frontal region again often characterised by line convection.

The evolution of the front in this way starts in the early stages of comma cloud development and has consequences on the subsequent development of the WCB of the system. In region ab, the WCB rises above the cold front in the classical ana-type (Sec. 2.2.2) configuration (Figure 3-4(b)). However, in region bcd, the air of the WCB is not forced to rise as steeply as in ab, since the surface cold front in this region has been bent back away from the main flow (to cd).

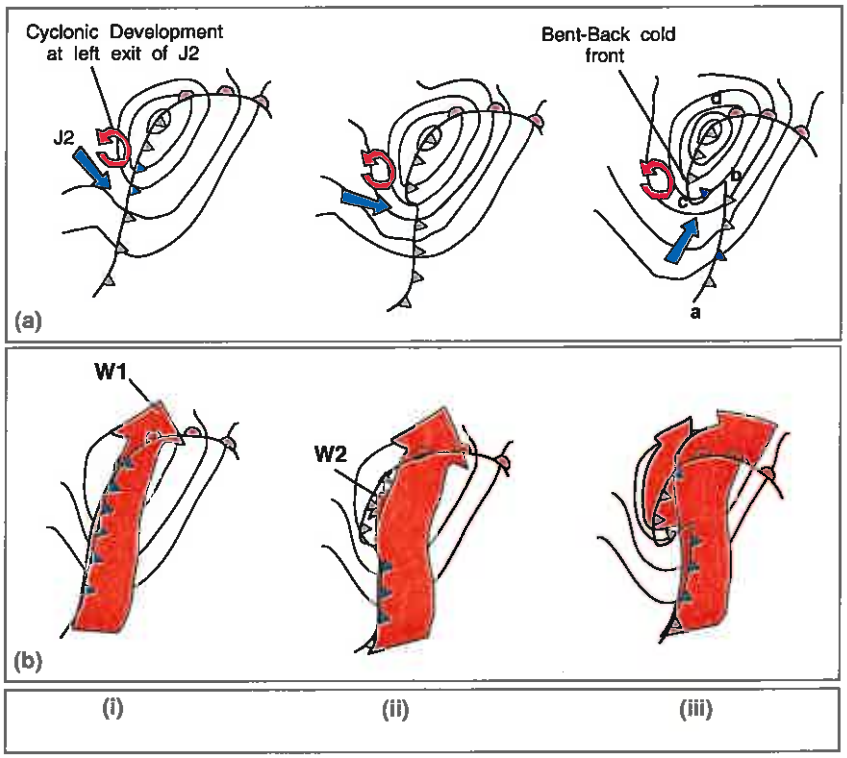


Figure 3-4 Two complementary processes [(a) and (b)] in developing the bent-back cold front structure of a mid-latitude cyclone. (a) The upper level cyclonic development region at the left exit of J2 is responsible for ***initiating*** *the bent-back structure of the surface cold front. Surface isobars are shown, with upper level jet J2 (blue arrow) and cyclonic development region (purple arrow). Letters a-d in [a(iii)] are referred to in the text. (b) Associated with the transverse ageostrophic circulation set up at the left exit of J2, W2 develops with a continued frictionally turned component to the west [b(ii)]. This continues until W2 reaches the main bent back cold front and ascends sharply, curving north [b(iii)]. Time between (i) and (iii) is typically 15-20 hrs.*

The WCB in the bent-back region of the cold front therefore ascends gradually in a 'shallow moist zone' within the boundary layer, experiencing friction at its base as it does so (Browning and Roberts, 1994). Thus *relative to the cold front* which is undercutting the conveyor belt, the motion of the conveyor belt's base is retarded, and a continuous frictionally turned component of the WCB is produced to the west.

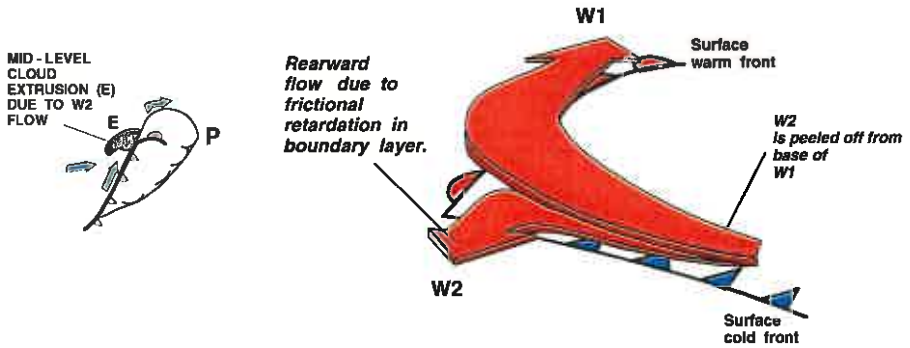


Figure 3-5 3D schematic of a developing mid-level cloud extrusion. W2 ascends sharply and has a rearward flow direction in the relative system due to friction in the boundary layer. W2 produces a mid-level cloud extrusion and will feed the cloud head with moisture. W1 continues to ascend as before.

This has the effect, that once the bent-back structure of the cold front has been initiated, *the original warm conveyor belt (WCB) is divided into two* (Young *et al.*, 1987) (W1 and W2). Thus whilst the southern portion of the WCB, W1 (characterised by e.g. θ_w ~ 17-19 °C) continues to ascend as before, the northern portion of the WCB in the bent-back region of the cold front, W2 (characterised typically by θ_w values a few degrees lower than W1 e.g. θ_w ~ 15-16 °C) is effectively peeled off in a westerly direction (Figure 3-5). Once W2 reaches the surface cold front of cd, it is forced to rise abruptly over it forming *a mid-level cloud extrusion.* The vigorous ascent of the W2 flow results in large amounts of precipitation in the region of the cloud extrusion corresponding to the cloud head.

As frontal waves may develop at any level of the troposphere and do not always extend through its full depth, comma clouds produced through the frontal wave process may or may not exhibit a mid-level cloud extrusion. However, mid-level cloud extrusions may sometimes be 'induced' by a separate cloud feature on the cold side of a leaf cloud. In such cases the close approach of the second feature provides a mechanism for the cloud extrusion process to begin – in effect the induction of a frontal wave on the polar front. In this case the cold air feature will be associated with a vorticity maximum on the cold side of J2 which also induces ascent on the cold side of the polar front cloud band when close enough.

3.2.3.3 Cloud Head development.

As the comma cloud develops, cold air just ahead of and beneath the warm front travels westward in the system-relative co-ordinate system. This cold air is the developing cold conveyor belt (Sec. 2.3) which eventually emerges to the west of the cloud band.

As the CCB flows west, it rises on an isentropic surface to ~500 mb until it emerges to the west of the WCB and north of the surface low. At this point, as the CCB ascends further, the flow of the CCB bifurcates :

- The northern branch of the CCB continues to ascend beyond ~400mb, and turns anticyclonically eventually merging with the WCB. Consequently, the highest clouds of the CCB are found in its northern extremity.

- The southern branch of the CCB stops ascending by ~500mb and turns cyclonically towards the cyclone's centre. In some cases this branch of the CCB is observed to descend at this altitude. Further development of the cyclone, in which cyclonic rotation increases, results in an increasing proportion of CCB being drawn southwards.

Lower altitude portions of the CCB are subject to frictional retardation in the boundary layer. This results in lower levels having a greater rearward component relative to the translational motion of the cyclone (see Sec. 3.2.3 for a similar case in the warm conveyor belt flow).

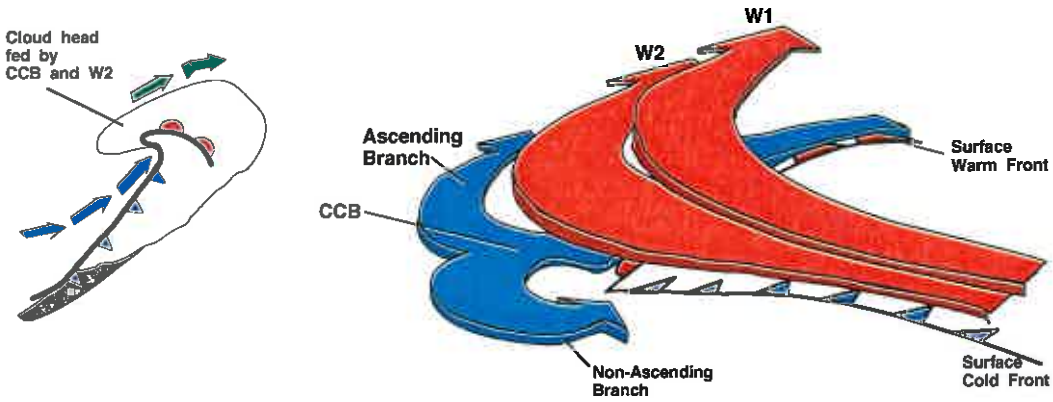


Figure 3-6 Schematic representation of the warm and cold conveyor belts present in a developing comma cloud. W1 is the main warm conveyor belt flow responsible for the body of the comma cloud. The lower part of this warm conveyor belt that peeled off at an earlier stage (W2) has developed sufficiently to feed the upper part of the comma cloud head. At this stage of the cyclone's life cycle, the CCB is extensive enough to move westward to the north of the warm front and beneath the warm conveyor belt flows. This flow completes the head of the comma cloud by the production of middle-level clouds. The positions of the jet streaks are shown in the schematic on the left: J1 (green arrows) and J2 (blue arrows).

Hence, lower levels of the CCB which are characterised by progressively lower values of θ_w, extend further west than those at upper levels with higher values of θ_w (Browning and Roberts, 1994). These lower flows emerge from beneath the warmer flows and can ascend to the top of the cloud head (Figure 3-7).

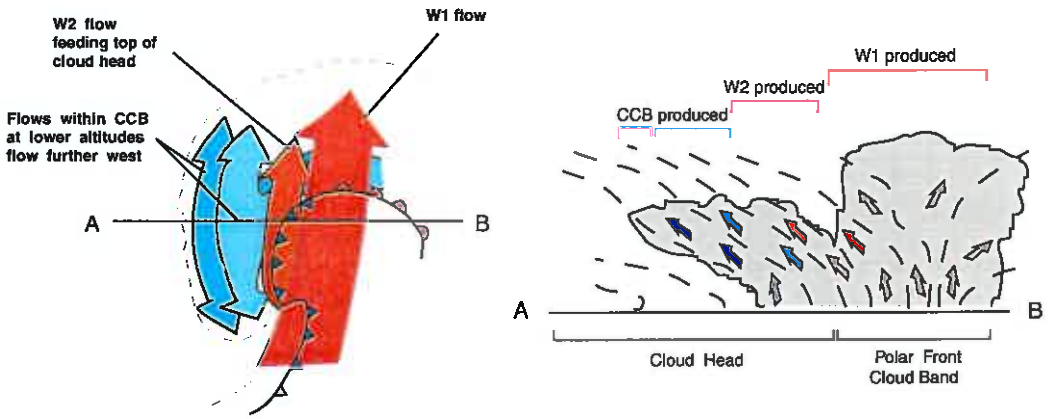


Figure 3-7 Lower portions of the cold conveyor belt flow further west in the relative system due to increased frictional retardation in the boundary layer. The cloud head (boundary indicated on figure) is thus fed by the W2 and CCB airflows. The bent-back cold front is clearly evident by this stage. The cross section shows that as the northern part of the CCB flows further west it also ascends to the top of the cloud head.

The behaviour of the CCB completes the information necessary to describe the structural change from type A to type B comma clouds of Bader et al. (1995). The W2, although originally only a mid-level cloud extrusion develops with time into the upper most layers of the cloud head. Progressively lower and more western layers of the cloud head are a result of the CCB.

3.2.4 Frontal Fracture and the Development of the Dry Slot

Further development of the comma cloud into a deep system generally requires the presence of J2 - frontal wave cyclogenesis built upon J1 alone is usually insufficient to produce any of the more advanced features portrayed in the conceptual models. In cases where J2 is present, the bent-back structure of the cold front (Sec. 3.2.3) develops so that its northern part stays attached to the warm front and to the north-west of the upper level jet J2, whilst the southern part is to the south-east of the upper level jet J2 (Figure 3-8). Both cold frontal regions associated with this *frontal fracture* are sharp at the surface and may have line convection associated with them (Sec. 2.2.2). However, the region of the cold front linking these two regions is more diffuse in nature.

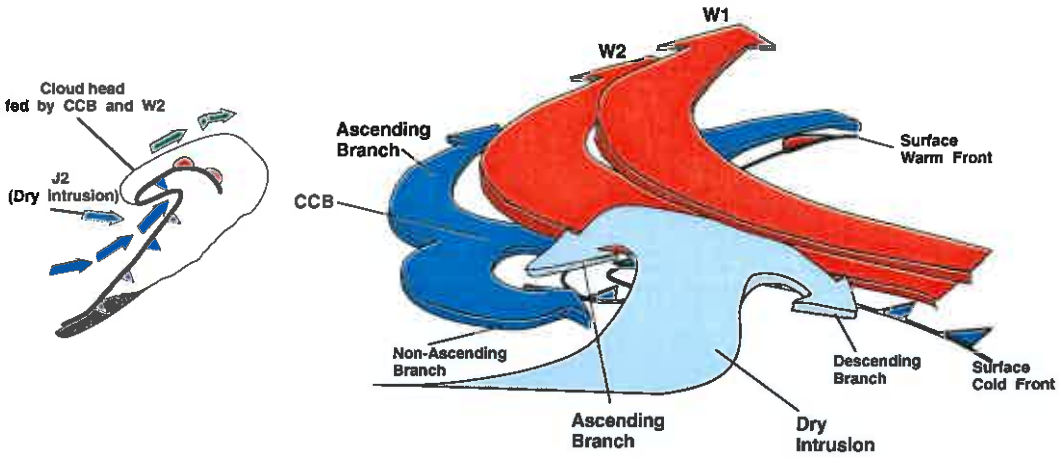


Figure 3-8 Schematic representation of the dry intrusion airstream in relation to the conveyor belt flows.

As frontal fracture is taking place, the circulation of the cyclone is increasing and the dry intrusion airstream (Jet J2) is descending rapidly towards the depression. This has the effect that the dry intrusion airstream is drawn further in to the circulation towards the cyclone centre and constitutes a cloud free region between the comma head and comma tail that is referred to as the *dry slot* or *dry tongue*. The position of the dry intrusion relative to the three conveyor belts of the comma-cloud is shown in Figure 3-8.

The dry slot indicates the leading edge of the ascending branch of the dry intrusion (i.e. the airflow in the left exit of the jet J2 in Figure 3-2), and may develop sufficiently to separate the cloud head from the polar-front cloud band in the region of frontal fracture (Figure 3-9). With the air of the dry intrusion being drawn deeper into the circulation of the cyclone it will soon cross the region of frontal fracture. In this region, the right-hand edge of the dry intrusion undercuts the higher cloud of the polar front cloud band and constitutes an upper cold front often in line with, but further north than, the surface cold front.

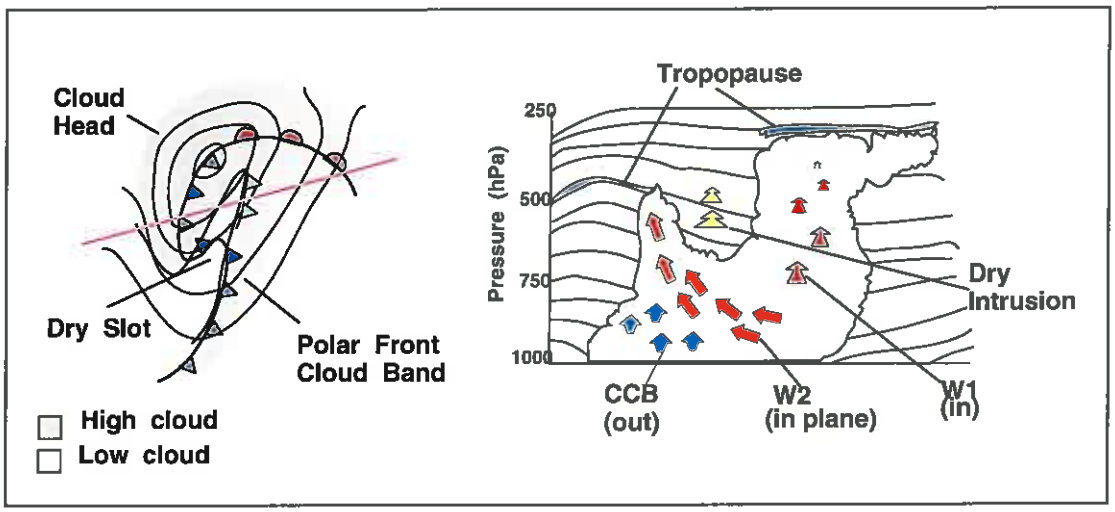


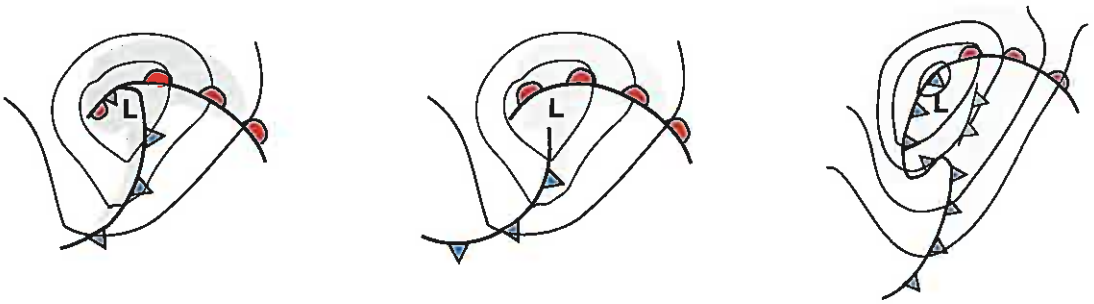
Figure 3-9 Conceptual model of a comma cloud, showing Cloud Head, Dry Slot and Polar Front Cloud band. The leading edge of the dry slot represents an upper cold front. The line across the comma cloud represents the area of vertical cross section shown on the right. The conveyor belts, once saturated, cross the lines of potential temperature (solid lines, shown) and rise along moist isentropic surfaces. The cloud head is fed by both the cold conveyor belt and W2, whilst the main body of the comma cloud is fed by the warm conveyor belt (W1). The dry slot is composed of air from the dry intrusion penetrating into the canopy of the comma cloud. In some situations convective clouds may develop from the W2 cloud into the dry slot, as shown in Figure 2-2. (Based on figures by Bader et. al., 1995).

Thus, this upper cold front is not a result of air from a surface cold front overrunning moist air from the warm conveyor belt (Sec. 2.2.3 and Sec. 3.2.5), but represents the leading edge of the dry intrusion air (Jet J2). This situation, in which the low θ_w air of the dry intrusion overlays the relatively high θ_w air of the CCB and W2 flows is potentially unstable, and convective clouds may develop from the air of the W2 into the air of the dry intrusion. This convection may produce significant mixing between the airstreams, and may be sufficient to trigger thunderstorms, especially in cases of rapid cyclogenesis. In some cases, the convective clouds may fill the dry slot entirely.

3.2.4.1 Frontal Analysis After Frontal Fracture.

In the traditional Norwegian frontal analysis a frontal wave develops with an occluded front to the north west of the low centre, signifying warm air aloft over a cold surface frontal zone. In the frontal analysis of Shapiro and Keyser (1990), the northern part of the fractured cold front becomes an extension of the warm front, facing away from the surface low pressure centre. Browning and Roberts (1994) propose a frontal analysis scheme in which the cold front after the fracture is represented as a continuous structure bending back on itself.

These different frontal analysis schemes highlight the difficulty in describing the frontal properties in the developing cloud head region. This *cloud-head frontal zone* is most precisely represented in the analysis scheme of Browning and Roberts (1994) which not only highlights the origins of the fracture but also better represents the sharp and diffuse regions of the cold front and the location of the dry slot with the upper cold front.



I) Traditional Norwegian configuration **II) Shapiro & Keyser** **III) Browning et. al.**

Figure 3-10 Frontal analyis schemes comparing that of (I) the traditional Norwegian model with those of frontal fracture by II) Shapiro and Keyser (Shapiro and Keyser, 1990) and III) Browning et. al., (Browning and Roberts, 1994). Scheme I represents the front to the north-west of the low as the beginnings of an occlusion. Scheme II has the origins of a bent-back warm front in the vicinity of fracture. Scheme III has a continuous s-shaped cold front at the fracture point, with a second upper cold front (shown) to the east of the low pressure centre.

3.2.5 Split Front Development.

At some point as frontal fracture takes place, with the air of the dry intrusion penetrating further into the cyclone, a point is reached in which the dry intrusion air starts to overrun the air of the W2 flow. This overrunning dry cold air therefore advances ahead of the surface cold front and appears as a well defined upper cold front (Figure 3-9). This process has been dealt with in more detail in Sec. 2.2.3.

3.2.6 Mature Vortex.

By the time the cyclone reaches this stage in its life cycle, the associated rotation extends through the whole depth of the troposphere; upper and lower vorticity centres have become vertically aligned with one another, resulting in a near-vertical structure to the vortex. The cloud band of the vortex may be continuous and spiral in towards the low pressure centre. This is accompanied by the system becoming slow moving.

4. Cyclone Classification.

4.1 Overview.

A classification of cyclones is based on the assumption that there exist characteristic cyclone types that exhibit systematic differences in their evolution and structure. The classification criteria of Young (1993) were identified at the start of Sec. 3 and yield seven different types, four of which are the result of the formation of a comma-cloud from the main polar-front cloud band. The seven types are

- ***Meridional trough*** cyclogenesis
- ***Confluent flow*** cyclogenesis
- ***Diffluent flow*** cyclogenesis
- ***Split flow*** cyclogenesis
- ***Instant occlusion*** cyclogenesis
- ***Cold-air*** cyclogenesis
- ***Induced-wave*** cyclogenesis

In Young's scheme, meridional trough, confluent flow, diffluent flow, and induced wave cyclogenesis all develop from the main frontal cloud band. Cold-air cyclogenesis develops from the cold air feature in isolation, whilst instant occlusion develops from the merging of a cold air feature and the polar front cloud band. Split-flow cyclogenesis develops from a comma cloud in the presence of two meridionally separated jet streams.

The following section summarises the different classes of cyclones as suggested in Young's scheme. Much of the information for this treatment was obtained from "Images in Weather Forecasting" (Bader *et al.*, 1995) and is included here with an emphasis on the jet streaks and conveyor belts discussed in Sec. 3. The main aim of this section however, is to identify the common features among the cyclone types so as to facilitate a more unified cyclogenesis perspective (Sec. 5).

4.2 Cyclogenesis Induced solely by the Synoptic Scale Airflow.

The following types of cyclogenesis all involve the development of a mid-level cloud extrusion from the polar front cloud band. The specifics of each case relate to the type of flow around the trough: whether symmetrical, confluent or diffluent, and this has a bearing on the specific formation of the emerging W2 flow.

However, in all three cases the presence of Jet J2 is essential to the initiation of the W2 flow and for cyclogenesis to begin. It is therefore suggested that these three cases may be viewed as variations on the common mechanism of a mid-level cloud extrusion initiated by the left exit of J2 which is then modified by the synoptic scale airflow.

4.2.1 Meridional Trough Cyclogenesis.

Meridional trough cyclogenesis occurs when a synoptic scale trough is present in the upper atmosphere and the airflow around the trough is symmetrical - i.e. there is no appreciable diffluence or confluence present at the entrance or exits of the trough.

A polar-front cloud band (F) is associated with a cold front zone downstream of the trough and develops as the result of a rearward sloping warm conveyor belt (W1)(Sec.2.2.2). Cyclogenesis occurs with the emergence of W2 and the associated development of a mid-level cloud extrusion (E). This develops (along with the CCB) into the cloud head of the comma cloud. The trigger for E (and therefore subsequent cyclogenesis) in this cyclone type is related to the presence of the left exit of Jet J2 as described in Sec. 3.2.3.2.

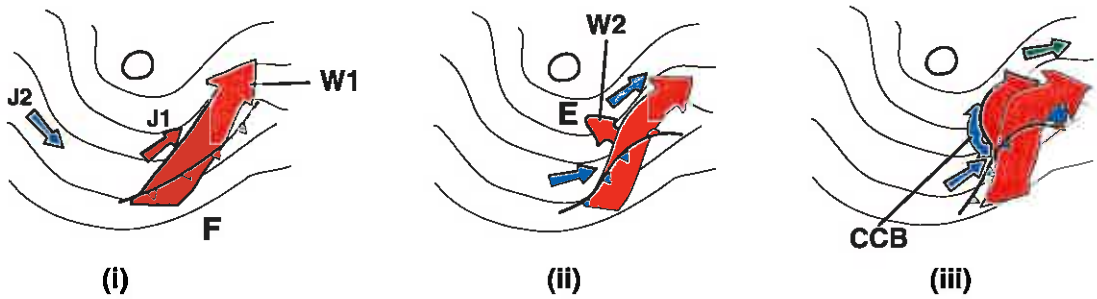


Figure 4-1 Meridional trough Cyclogenesis is associated with a cold front at the leading edge of a synoptic scale upper trough (i). A mid-level cloud extrusion (E) develops from the W2 flow (ii) which feeds the upper part of the cloud head. At later stages (iii), the cloud head is also fed with the cold conveyor belt (CCB). Jets J1 and J2 are shown. (After Bader et. al, 1995).

It should be noted that Bader *et al.* (1995) represents the jet moving round the symmetrical trough as a single continuous jet streak. Using the convention described in Sec. 3.1, the system is broken up into two jet streaks of close proximity, and the role of J2 in the initiation of the W2 flow is then more apparent as it rounds the base of the trough. However, this consideration is still consistent with the treatment of Bader *et al.* who describe the arrival of a short wave trough at the onset of W2.

4.2.2 Confluent-Flow Cyclogenesis.

An upper trough with confluent flow downstream of the trough axis may develop a mid-level cloud extrusion (E) on the poleward side of the polar front cloud band (F). In this case, the cloud extrusion will be significantly elongated in the direction of flow around the trough.

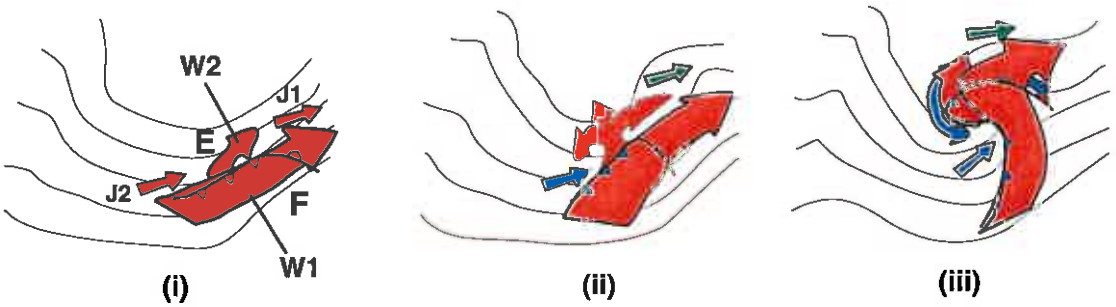


Figure 4-2 An elongated region of cloud (E) associated with the W2 flow (or sometimes a remnant of an old front) lies poleward of the polar front cloud band (F) (i). Often, F will have a double frontal structure (Bader et. al, 1995). E then expands and develops a convex edge (ii), but with dry intrusion between it and the polar front cloud band. As depression deepens, the cloud head develops further (iii). Jets J1 and J2 are shown. (After Bader et. al, 1995).

However, the arrival of Jet J2 (or the arrival of a secondary vorticity maximum) is still essential in order to focus the ascent of W2 into a more limited area and to trigger cyclogenesis. The development of the cloud from the W2 flow into a well defined broad system with a convex edge results in a prominent cloud head, separated from the polar front cloud band by the dry slot. This class of cyclone is often specifically referred to as the *cloud head* type, although in general the term describes the feature common to many types of cyclone, and not specific to confluent-flow cyclogenesis.

4.2.3 Diffluent-Flow Cyclogenesis.

An upper trough with zonal flow upstream of its axis will induce cyclogenesis if there is marked diffluent flow in its downstream region. The trigger for cyclogenesis is again the ascent in the left exit of the jet streak (J2) moving through the diffluent downstream region of the trough. This ascent manifests itself as the emergence of the W2 flow and produces a mid-level cloud extrusion (E).

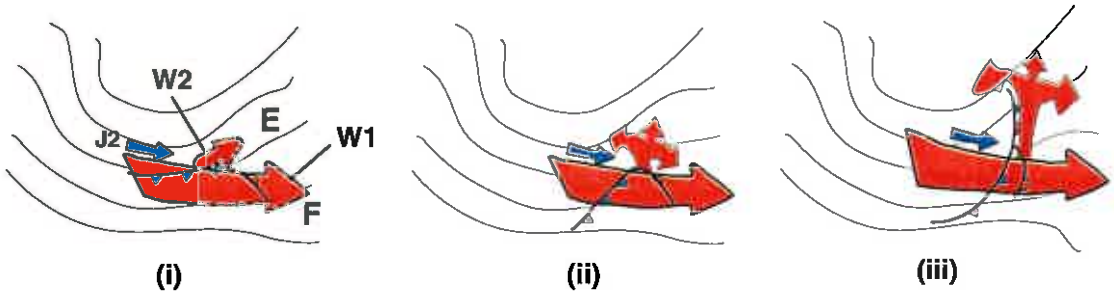


Figure 4-3 Diffluent Flow Cyclogenesis occurs when there is marked diffluent flow in the downstream region of a synoptic scale upper trough. The initiation of the W2 flow is associated with the left exit of the jet streak moving through the diffluent region (i). The strongly ascending W2 flow then expands in a meridional direction (ii) until it becomes highly elongated (iii). Dry Intrusion air is normally drawn into the system at stage (ii) so that this type of cyclone usually possesses a strong cloud hook and a split front at the rear edge of the W2 flow. Jet J2 is shown. (After Bader et. al, 1995).

According to Young's scheme, this type of cyclogenesis does not appear to require the presence of Jet J1, and so the polar front cloud band (F) is not shaped into a leaf cloud in the initial stages. However, this serves to illustrate the relative importance of the two jet streams in cyclogenesis: J2 is alone sufficient to initiate cyclogenesis by inducing the mid-level cloud extrusion. It should be noted however, that due to the diffluent flow in the trough, this type of cyclone develops with a cloud head more elongated at right angles to the flow (i.e. in a meridional direction) than in other cases. Also the flow is such that dry air aloft penetrates deeper into the cyclone than in other cases, and split front development is rapid. Although this results in a more distorted comma cloud, the fundamental airflows within the system are common to other types of cyclogenesis discussed elsewhere.

4.3 Cyclogenesis induced by the Merging of two Cloud Features

The following two types of cyclogenesis (instant occlusion and split-flow) both involve the merging of two initially separate entity cloud systems into a single developing cyclone. Split-flow cyclogenesis is unique in that it also has some aspects relating to synoptic airflow considerations as well (requiring two meridionally separated jet streaks). However, it is suggested that Split-flow and instant occlusion cyclogenesis are best viewed together as they both involve the development of two cloud systems

with pronounced baroclinicity (one in the cold air upstream associated with J2 and the other downstream associated with J1) and their subsequent merging.

4.3.1 Instant Occlusion Cyclogenesis.

If the cold air feature associated with Jet J2 rounds the base of the upper trough and approaches within 300km of the polar front cloud band, the two systems may merge. The resulting cloud formation resembles the classical occlusion of a mature depression, without the occlusion process (cold air undercutting the warm air of the depression and lifting it aloft).

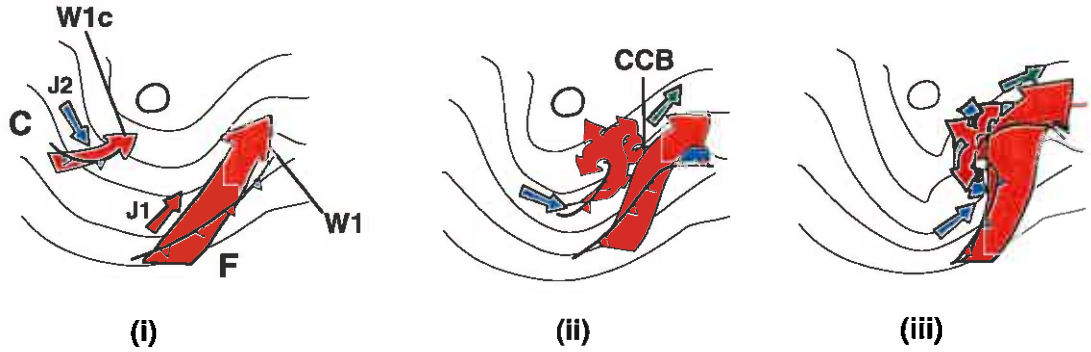


Figure 4-4 Instant occlusion cyclogenesis occurs when a cold air feature upstream (i) rounds the base of an upper trough and merges with a polar front cloud band downstream. The W1c flow associated with C is forced to ascend strongly over the cold air of the CCB (ii) and convective clouds may arise in the gap between W1c and W1 due to convective instability. Eventually (iii), a complete merging of the systems produces the comma cloud. Jets J1 and J2 are shown. (After Bader et. al, 1995).

This type of cyclogenesis is a relatively common occurrence and may be interpreted in terms of a dual-conveyor-belt configuration (Browning and Hill, 1985 and McGinnigle *et. al.*, 1988).

4.3.2 Split-Flow Cyclogenesis.

Split Flow cyclogenesis (originally proposed by Weldon (1975)) is the rarest form of cyclone development, as it often requires local topography to trigger a double jet with a split flow configuration - i.e. it occurs to the east of mountain ranges (Bader. *et. al.*, 1995).

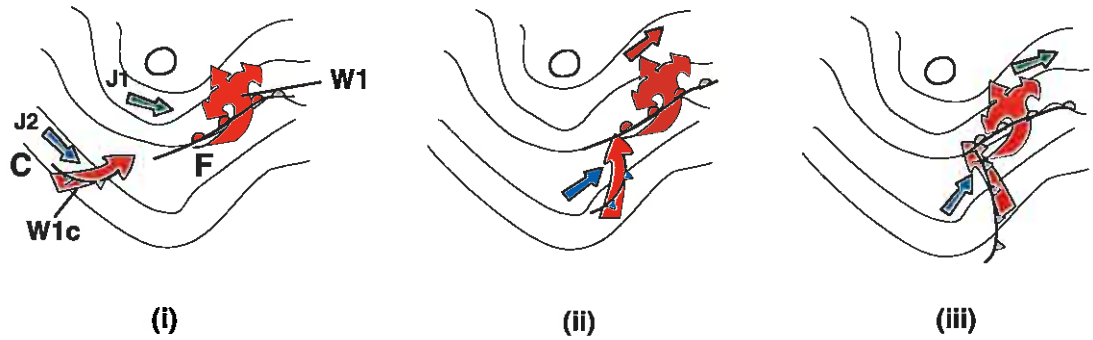


Figure 4-5 Split-flow cyclogenesis may be induced to the east of mountain ranges where two jet streams are present around the base of an upper trough. The cloud feature F (associated with the W1 flow) is produced in the deformation region at the leading edge of the trough (i). A second cloud structure, C develops in the southern part of the trough, and rounds its base (ii). The two cloud features merge (iii) to form a large comma cloud. Jets J1 and J2 are shown. (After Bader et. al, 1995).

The jets are separated in a meridional direction - one poleward and one equatorward. The cold air feature upstream of the main trough develops in the

equatorward jet, whilst the second cloud formation develops in the deformation zone ahead of the trough.

The main difference between this and instant-occlusion cyclogenesis is the position of the jets in the initial stages; with J1 originating to the north of J2 rather than to the south-east. However, once C rounds the axis of the trough, the jets take on their more familiar orientation with J1 poleward of F and J2 to the west of F.

4.4 Cyclogenesis Induced by a Cold air Feature

This type of cyclogenesis involves the development of a cold air feature upstream of the trough axis (exhibiting little baroclinicity), which then induces cyclogenesis in the polar front cloud band.

4.4.1 Induced-Wave cyclogenesis

Induced-Wave cyclogenesis involves a polar trough approaching to within 300km of the polar front, but without any merging of the two systems. The presence of the polar trough is such that it induces a cloud extrusion (E) in the polar front and therefore initiates cyclogenesis where the main thermal gradient is located (beneath the polar front, F). The cloud extrusion (W2) may be a separate entity, or originate from the lower layers of W1. The cloud feature associated with the polar trough remains a separate entity throughout the process until it eventually dissipates at the later stages of cyclogenesis.

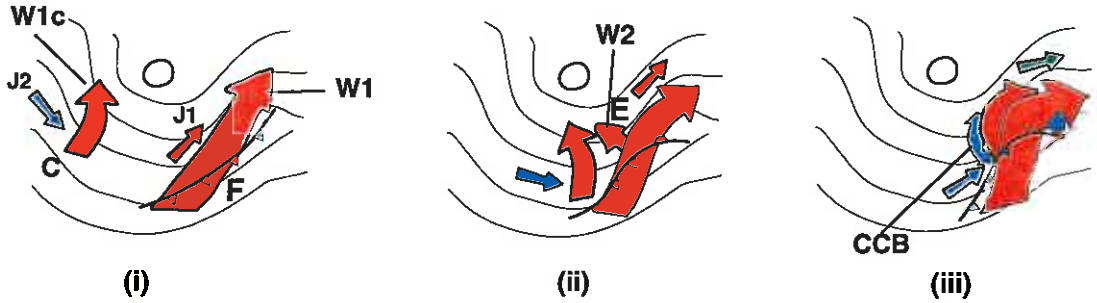


Figure 4-6 Induced wave cyclogenesis requires that a cold air feature (C) rounds the base of the upper trough (i) and approaches the polar front cloud band. The presence of C induces a mid-level cloud extrusion (E) in the polar front cloud band (ii) and the process continues identically to that of meridional trough cyclogenesis (iii). Note that C in this case possesses little baroclinicity. Jets J1 and J2 are shown. (After Bader et. al, 1995).

The development of the cyclone of the induced-wave type is identical to that of Meridional Trough cyclogenesis (Sec. 4.2.1).

4.5 Cyclogenesis Solely in a Cold air Feature

This type of cyclogenesis involves the development of a cyclone out of a cloud system originating upstream of the trough axis. For this type to occur, the cloud feature must posses strong baroclinicity.

4.5.1 Cold-Air Cyclogenesis.

Evidence from satellite imagery (Bader *et. al.*, 1995) suggests that if the distance of closest approach between the cold air feature and the polar front cloud band is greater than 300 km, then the cold air feature is likely to develop alone (*Cold Air Cyclogenesis*).

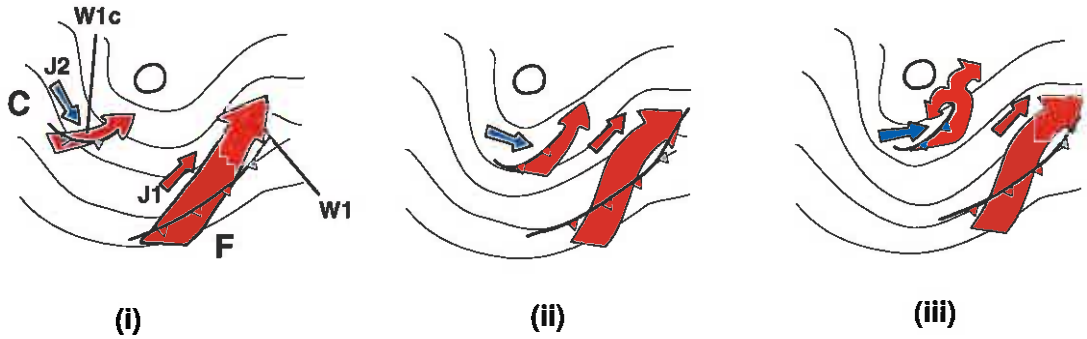


Figure 4-7 Cold air cyclogenesis is initiated by the development of a cold air feature upstream of the axis of an upper trough (i) and is associated with a warm conveyor belt (W1c). C moves ahead of the axis of the trough and expands due to ascent (ii), developing into a comma shape (iii). F may then start to dissipate. Jets J1 and J2 are shown. (After Bader et. al, 1995).

The area of enhanced cumulus develops independently into a comma cloud as it rounds the base of the upper trough (See Sec. 3.2.1.1).

5. Unification

5.1 Overview

This review has been divided into two major parts: (i) the treatment of a weather system in terms of its primary airflows (Sec. 2 and 3), and (ii) the recognition of differences from cyclone to cyclone resulting in the classification scheme of Young (Sec. 4).

The hypothesis to be discussed here is built upon the location and properties of the dry intrusion airstream (jet J2) relative to a polar front cloud band downstream of a synoptic scale upper trough axis (to be discussed in Sec. 5.3). This scheme uses a similar approach to Browning and Hill (1985) in which three types of cyclogenesis were identified according to the distance between the area of enhanced cumulus and a pre-existing polar-front cloud band. However, the following section will show that by exploiting the knowledge of a system's evolution (Sec. 3) and the information of Young's scheme, a unification of Young's seven classes of cyclone into a continuum of cyclone types is possible.

5.2 J2 and the importance of convective cloud formation

As detailed earlier, J2 represents the upper-tropospheric wind maximum of the cold polar air being brought south in the upstream region of the trough and has the additional association with high potential vorticity (a consequence of its proximity to the lower stratosphere).

Although the dry intrusion itself is a non-cloud producing airflow, its association with the cold air of the polar trough, its movement over relatively warm oceans, and the region of ascent associated with the upper level PV maximum combine to provide ideal conditions for convection to occur. The relationship of J2 with convective cloud formation is therefore well established and is discussed in Sec. 3.2.1.1 and by e.g. Reed and Blier (1986), Zillman and Price (1972) and Browning and Hill (1985). Figure 5-1 summarises the evolution of a cold air feature at the leading edge of J2.

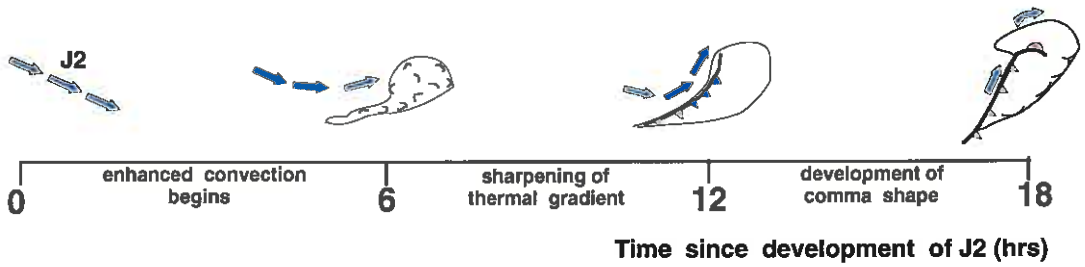


Figure 5-1 Providing the polar front cloud band is sufficiently far away that convection can be initiated, convective clouds may build up in the cold air associated with J2. Although many factors then contribute to the likelihood of convection, the time scale gives an indication of how long it can take for convection to build into a comma cloud. For the example shown, 18 hrs would be typical of more rapid cyclogenesis cases.

The importance of these results is that *given sufficient time to do so*, convective cloud (C) will develop in the cold air associated with J2. C will only develop further once it has rounded the thermal axis of the trough, as convection restricted to the trough's cold side is likely to be suppressed by subsidence associated with anticyclonic development.

5.3 Time to interaction

As discussed in Sec. 3.1, jet streaks J1 and J2 are relatively short-lived cores of high winds in comparison with the long-lived jet stream. Because of their association with a particular synoptic flow pattern, J1 and J2 will develop by gradually increasing in intensity until their cores reach some maximum wind speed, then die off over a period typically of a few days. However, in any given synoptic situation a newly developed[5] J2 may be a varying distance away from a polar front cloud band, P. As six of the seven types of cyclogenesis detailed in Young's scheme involve this polar front cloud band (the seventh being cold-air cyclogenesis, Sec. 4.5.1), this clearly has repercussions for the time available for a cold air feature to evolve as a purely cold air phenomenon. Figure 5-2 identifies four major *relative* distances (d) apart of J2 and P, which are simply termed large, medium, small, and nil. It can be clearly seen that the further away J2 is, the more developed the cold air feature can become before it interacts with P.

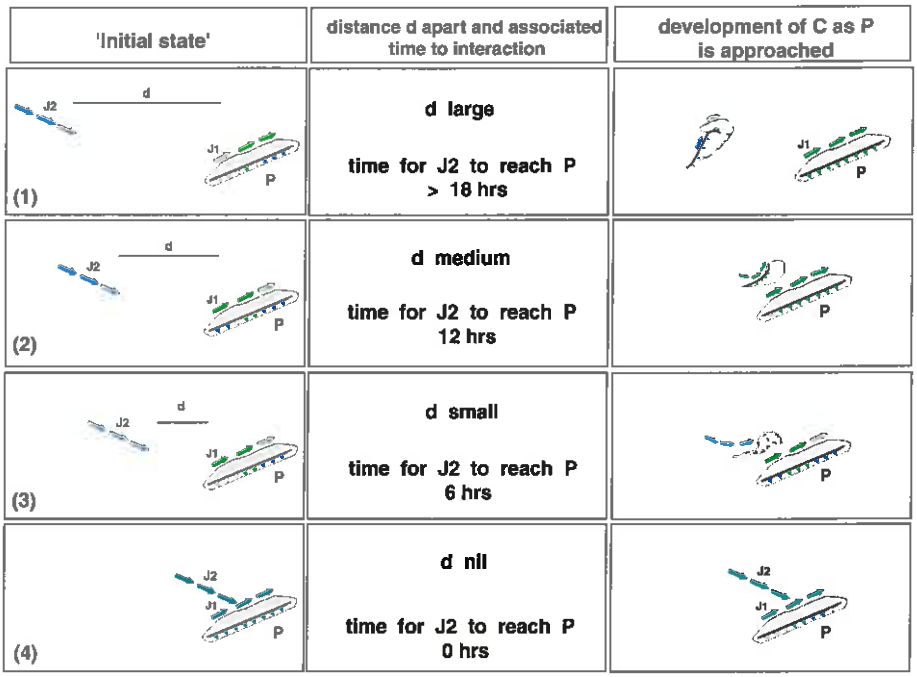


Figure 5-2. The distance away that J2 develops from the frontal cloud band (P), is related to the available time for enhanced convection (C) to be initiated. A time ~ 18 hrs may be sufficient for the thermal gradient of C to be enhanced and the development of a cloud head thus producing a comma cloud in the cold air. Distances less than this will produce cold air features of progressively less development (compare time available with Figure 5-1).

In this hypothetical consideration, there are two extremes immediately apparent (1 and 4) with two intermediate stages (2 and 3).

1. When d is large, J2 develops a large distance away from P and may not reach it for over 24 hours. C can evolve into a comma cloud during this time.
2. For medium values of d, J2 develops far enough away from P so that C grows into a well-defined region of cloud possessing a well developed

[5] A way of precisely defining this state is necessary and is the subject of future work. However, it is anticipated that a minimum threshold in wind speed of the jet core may provide one way of establishing the development of J2. A second method would be to treat the evolving system in terms of its potential vorticity distribution and to describe J2 within this framework.

thermal gradient. However, C does not possess any significant comma cloud shape.

3. For small d, J2 develops close enough to P so that C can grow only to an ill-defined clump of cloud. In this case C will exhibit little or no thermal gradient.

4. When d is nil, J2 develops immediately next to the frontal cloud band so that C has no opportunity to develop at all. There is a complete absence of a cold air feature and cyclogenesis occurs solely in the polar front cloud band.

In the unified scheme to follow, it is the degree to which C has developed before interaction with P that determines the mode of cyclogenesis that is most likely.

5.4 The cyclogenesis spectrum

The unified scheme developed here views cyclogenesis as a continuum of types. The parameter is the initial distance apart of J2 (when newly developed) from P and this dictates the subsequent degree of development of a cold air feature. As stated earlier, it is then the maturity of C that produces the cyclogenesis characteristics observed and categorised by Young.

Figure 5-3 presents the scheme within the context of a continuously evolving system. Branches in the top left of the figure allow for the degree of development of C: the green branch corresponds to no development of C (J2 close to P), whilst progression through the orange, red and blue branches represents increasing maturity of C. To use the diagram, choose the appropriate distance between J2 and the polar front cloud band in the top right hand corner (close, intermediate and far) and choose the degree of development of C (no convection, non-baroclinic, baroclinic, comma cloud) on the left hand side. The intersection of the two paths then indicates the mode of cyclogenesis available for the developing storm.

The classes of Young's scheme are born out within the unified scheme:

- Blue line. A system in which C has developed to maturity without interacting with the polar front - consistent with Young's 'cold air cyclogenesis'.

- Red line. A system in which C, before interacting with the main polar front, has developed in the cold air mass to a well-defined stage with an associated thermal gradient - consistent with Young's 'instant occlusion' and 'split flow' types.

- Orange line. A system in which C has developed no further than a small clump of convective cloud before the upper level PV interacts with the polar front - consistent with Young's 'induced wave' cyclogenesis.

- Green line. A system in which J2 develops close to the polar front and is influential in shaping the cloud structure in the immediate vicinity of the polar front cloud band - consistent with Young's 'meridional trough', 'confluent flow' and 'diffluent flow' cyclogenesis.

- Magenta line. Cyclogenesis due to the development of a frontal wave on the polar front. As this type of cyclogenesis does not require the presence of J2, cyclones produced by this mechanism generally do not exhibit any severity and longevity. *Only with the arrival of J2 at a later stage will the cyclone develop to the more advanced system shown in the lower part of the figure.* Cyclogenesis of this type is not included in Young's scheme.

The branches converge when the common characteristics between the developing cyclones are sufficient to generalise into a single hybrid comma-cloud exemplifying

the final stage in the evolution of all types at this stage. However, it should be noted that the precise shape of the comma cloud will strongly depend on the flow pattern around the base of the upper trough, and variation of this idealised view is probable.

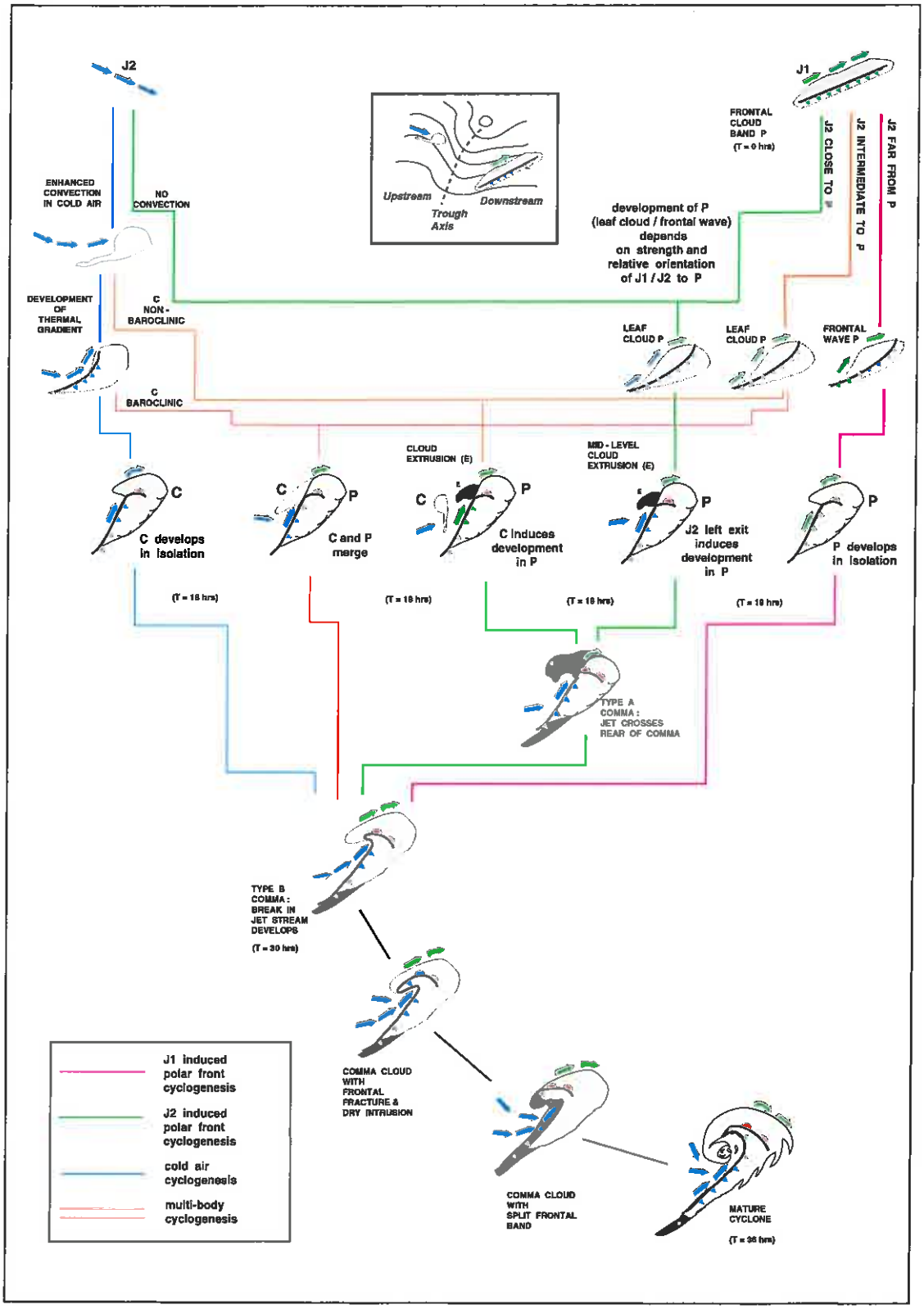


Figure 5-3. The life cycle of a midlatitude cyclone. The synoptic setting is a synoptic scale upper trough with jet streaks J1 and J2. A cold air feature may interact with the polar front cloud band in different ways depending on its stage of development. This produces the different classes of cyclones. See text for further details.

The system will have J2 pushing far into the region between the comma head and polar front cloud band, with the remains of J1 now reduced to the top of the head only. With further development the cold front fractures within the region of the cloud head and J2 is drawn further into the circulation of the depression forming the dry slot. Eventually the right hand edge of the dry intrusion overruns the surface cold front and constitutes an upper cold front. After approximately 36 hours the cyclone reaches its mature stage with its near-vertically aligned rotation extending through the whole depth of the troposphere.

6. Closing Remarks

Conceptual models are the embodiment of complex physical processes and represented within a simple, flexible framework. This report has shown that a detailed structural model exists for every stage in a cyclone's life cycle, and that each synoptic setting merely distorts the fundamental airflows of the system. The important thing about conceptual models therefore, is that they are adaptable to the continuously changing conditions of the troposphere and are a major tool in the treatment of cyclogenesis.

The unified view of cyclogenesis developed in this report allows for a more relaxed classification of cyclones and permits intermediate cases with properties of more than one type to be considered. It also allows cyclogenesis cases to be viewed as different manifestations of the more fundamental phenomena of distinct airflows in the system. This has the added advantage that the emphasis shifts from different types of cyclones to the WCB, the CCB, the jet streaks and the dry intrusion of the system. It should not be forgotten however, that the two approaches are in fact two aspects of the same analysis: the unified view suggested here is merely another way of viewing Young's scheme, and their relative merits will strongly depend on their proposed application.

The unification scheme proposed in Sec. 5 attempts to draw together many strands of work developed over the last decade or so into a *working hypothesis* of cyclogenesis unification. However, further work is necessary to rigorously test this view of cyclogenesis, and it is hoped that the FASTEX experiment will provide an ideal cross-section of cyclogenesis cases in which to do so.

The location, intensity and development of jet streaks are clearly of major importance to the success of this scheme. It is anticipated that some minimum threshold of wind speed could be established from which to determine if a jet streak has been 'created' and from which a significant effect on cyclogenesis would result.

One disadvantage of treating jet streaks solely in terms of their wind speed is that shear and curvature factors within the synoptic scale flow may complicate their diagnosis. However, it has been shown in this report that the jet streaks have a close relationship with potential vorticity – high PV being on the poleward side of the jet and influencing much of the development of a cyclone through the dry intrusion airstream. Perhaps a more robust definition of jet streaks could therefore result out of their treatment in terms of PV.

In the scheme, the separation distance between the jet J2 and the polar front cloud band influences the mode of cyclogenesis that is most likely. However, this does not account for wide variations in the speed of propagation of J2 brought about by the strength or amplitude of the upper trough. One way to overcome this problem would be to consider the distance between J2 and P as along the streamlines, rather than the perpendicular distance between the two features. An estimate of the propagation speed of J2 when 'newly developed' could then be assumed to be constant, and an interaction time calculated.

Despite these foreseen problems, the unified scheme has one major advantage which necessitated its development: with the reduction of cyclogenesis to the interaction (or not) of a number of component elements, the way is paved for a cyclone's more versatile description and diagnostic assessment. Of particular interest would be the use of potential vorticity to describe these 'cyclone building

blocks' since this would facilitate a more consistent integration of the conceptual model into Numerical Weather Prediction.

Although their use by forecasters in the interpretation of satellite imagery is well established, it is felt that great potential exists for further applications of conceptual models. An evaluation of conceptual models with a view to their application to NWP will be dealt with in a following JCMM internal report.

7. Acknowledgements

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8. References.

Bader M.J., Forbes G.S., Grant J.R, Lilley R.B.E and Waters A.J 1995 : Images in Weather Forecasting, Cambridge University Press.

Bergeron T. 1937 : On the Physics of Fronts, *Bull. Amer. Meteor. Soc.*, **18**, 265-275

Bjerknes J. and Palmen E., 1937 : Investigations of Selected European Cyclones by Means of Serial Ascents. *Geofys. Publ.*, 12, No. 2 1-62

Browning K.A. 1990 : Organisation of clouds and Precipitation in Extratropical Cyclones, *Palmen Memorial Volume., American Met. Soc.*, 129-153

Browning K.A. 1994 : Life Cycle of a Frontal Cyclone, *Met. Apps.* **1**, 233-235

Browning K.A., Ballard S.P. and Davitt C.S.A 1997: High Resolution Analysis of Frontal Fracture, *Mon. Wea. Rev.*, **125**, 1212-1230

Browning K.A. and Hill F.F., 1985 : Mesoscale Analysis of a Polar Trough Intersecting a Polar Front, *Q.J.R.Meteorol. Soc.*, **111**, 445-462

Browning K.A. and Monk G.A. 1982 : A Simple Model for the Synoptic Analysis of Cold Fronts, *Q.J.R.Meteorol. Soc.*, **108**, 435-452

Browning K.A. and Roberts N.M. 1994 : Structure of a Frontal Cyclone, *Q.J.R.Meteorol. Soc.*, **120**, 1535-1557

Browning K.A., Roberts N.M. and Illingworth A.J. 1997 : Mesoscale Analysis of the Activation of a Cold Front During Cyclogenesis, *Q.J.R.Meteorol. Soc.*, **123**, 2349-2375

Browning K.A. and Roberts N.M. 1996 : Variation of Frontal Precipitation Structure Along a Cold Front, *Q.J.R.Meteorol. Soc.*, **122**, 1845-1872

Carlson T.N. 1980 : Airflow Through Midlatitude Cyclones and the Comma Cloud Pattern, *Mon. Wea. Rev.*, **108**, 1498-1509

Danielsen E.F., 1966 : Research in Four-Dimensional diagnosis of Cyclonic Storm Cloud Systems, Sci. Rep. No. 1, Contract AF19(628)-4762, Penn. State Univ.

Evans M.S., Keyser D., Bosart L.F. and Lackmann G.M. 1994 : A Satellite-Derived Classification Scheme for Rapid Maritime Cyclogenesis, *Mon. Wea. Rev.*, **122**, 1381-1416

Harrold T.W., 1973 : Mechanisms Influencing the Distribution of Precipitation Within Baroclinic Disturbances, *Q.J.R.Meteorol. Soc.*, **99**, 232-251

Keyser D. and Shapiro M.A. 1986 : A Review of the Structure and Dynamics of Upper-Level Frontal Zones, *Mon. Wea. Rev.*, **114**, 452-499

McGinnigle J.B., Young M.V. and Bader M.J., 1988 : The development of instant occlusions in the North Atlantic. *Meteor. Mag.*, **117**, 325-341

McLennan N. and Neil L., 1988 : Marine Bombs Program (Phase II). Atmospheric Environment Service Pacific Region Tech. Rep. 88-002.

Meteorological Glossary, 1995 : U.K. Meteorological Office.

Neiman P.J. and Shapiro M.A., 1993 : The Life Cycle of an Extratropical Maritime Cyclone. Part I : Frontal-Cyclone Evolution and Thermodynamic Air-sea Interaction, *Mon. Wea. Rev.*, **121**, 2153-2176

Petterssen S. and Smebye S.J. 1971: On the development of extratropical cyclones. *Q.J.R.Meteorol. Soc.*, **97**, 457-482

Reed R.J. and Blier W 1986 : A Case Study of Comma Cloud Development in the Eastern Pacific, *Mon. Wea. Rev.*, **114**, 1681-1695

Shapiro M.A. and Keyser D., 1990 : fronts, Jet Streams and the Tropopause *Palmen Memorial Volume., American Met. Soc.*, 167-191

Weldon R.B., 1975 : The structure and evolution of winter storms. Satellite training course notes, part II (Washington, D.C., Satellite Applications Division, NOAA/NESDIS)

Weldon R.B., 1986 : Synoptic Scale Cloud Systems. In P.S Parke (ed.), Satellite Imagery Interpretation for Forecasters, Temple Hills, Md., National Weather Association, Meteorological Monographs 2-86, **1**, pp. 2.A.1-35

Young M.V., Monk G.A. and Browning K.A. 1987 : Interpretation of Satellite Imagery of a Rapidly Deepening Cyclone, *Q.J.R.Meteorol. Soc.*, **113**, 1089-115

Young, M.V. 1993: Cyclogenesis: interpretation of satellite radar images for the forecaster. *Forecasting Research Division tech. Report* **73** (Bracknell, UK, Meteorological Office), unpublished

Young M.V.,1997 : Extratropical cyclones - a forecaster's perspective, *Meteorol. Appl.*, **4**, 293-300

Zillman J.W., and Price P.G. (1972): On the thermal structure of mature Southern Ocean cyclones, *Australian Meteorological Magazine.*, **20**, 34-48

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Met Office Joint Centre for Mesoscale Meteorology Department of Meteorology
University of Reading PO Box 243 Reading RG6 6BB United Kingdom
Tel: +44 (0)118 931 8425 Fax: +44 (0)118 931 8791
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